THE NEBULAR HYPOTHESIS.[1]

By R. G. Aitken.

....The general consensus of opinion for more than a century has been that our Sun and its system developed into its present form from an earlier nebular state. In fact, the harmonious relations, independent of gravitation, that are actually observed in the planetary system point incontrovertibly to a common origin, and that this primitive form was a nebula is postulated by all theories. Even the meteoritic hypothesis, with which Lockyer's name is identified, does not contradict this assumption, for the aggregation of meteorites from which he derives the system must, dynamically at least, be identical with a nebula, as Darwin has proved. The various theories differ, however, quite radically as to the primitive form and physical conditions of the nebula and as to the processes of development into the present planetary system.

Our immediate concern is with the specific theory advanced by Laplace in 1796, and in more elaborate form in 1808,—a theory that has been characterized as "perhaps the most beautiful and fascinating and one of the boldest speculations ever offered in any science," and one that has profoundly influenced the progress of thought in the nineteenth century.

Laplace assumed a nebula of intensely heated gas which by the influence of gravitation had become approximately spheroidal in form and rotated slowly upon an axis practically like a solid body,—the outer portion, that is, moving more rapidly than the inner parts. This nebula, extending far beyond the orbit of the outermost planet and subject practically to the action of no external forces, gradually contracted by its own gravitation, the angular rotatory velocity necessar-

[1] This article is a portion of a lecture delivered before the class in modern astronomy at the University of California on March 17, 1906. It is here printed because it contains a brief resume of recent important articles by Professors Chamberlin and Moulton questioning the validity of the Laplacian theory of planetary evolution, and outlining a substitute based upon the assumption of an original spiral nebula. These articles are:

"An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," by F. R. Moulton, "Astrophysical Journal," Volume XI, p. 103, 1900.

"On the Possible Function of Disruptive Approach in the Formation of Meteorites, Comets, and Nebulae," by T. C. Chamberlin, "Astrophysical Journal," Vol. XII, p. 17, 1900.

"Fundamental Problems of Geology," by T. C. Chamberlin, Year Books, Nos. 2, 3, and 4, Carnegie Institution of Washington, 1903, 1904, 1905.

"On the Evolution of the Solar System," by F. R. Moulton, "Astrophysical Journal," Vol. XXII, p. 165, 1905.

Also articles by Professor Chamberlin in the "Journal of Geology."

ily increasing and the polar diameter diminishing as it contracted, until the centrifugal forces at its boundary balanced the attraction of the central mass. Then an equatorial ring was abandoned, the rest of the matter continuing to contract. By successive repetitions of this process other rings were left behind, and these rings, being in general in unstable equilibrium, could not maintain themselves as rings, but, slowly collecting, eventually formed the nearly spherical masses of the planets. These in turn, or at least some of them, by similar processes abandoned rings, which in time became satellites.

In this specific form the theory commanded immediate and almost universal acceptance. Difficulties indeed it encountered at once, and in course of time various modifications were suggested, and more or less approved, to account for the observed facts that were inconsistent with LAPLACE's formulation. For example, the retrograde motion of the satellites of *Uranus* and *Neptune* and the rapid motion of the inner satellite of *Mars* were anomalies that demanded explanation. Again, it was evident, when the mechanical equivalent of heat was discovered and the principle of the conservation of energy established, that the high initial temperature assumed by LAPLACE was not essential. The potential energy of the separated particles of the nebula would afford a sufficient explanation of the present temperature of the Sun.

But though beset by difficulties and subject to modification in various details, the hypothesis in its essential features held its place throughout the century. It was accepted by men like HELMHOLTZ, KELVIN, NEWCOMB, and DARWIN, and was taken as the basis of all the calculations that have so far been made as to the age of the Sun, the amount of the Sun's heat and radiation, and the probable duration of the system in its present form, calculations obviously of the most fundamental importance in geology as well as astronomy.

The critics of the theory, however, gradually multiplied and brought forward ever stronger facts and arguments for its overthrow. More than forty years ago M. BABINET showed that when the nebula filled the orbit of *Neptune* more than 27,000 centuries would have been needed for a single revolution, and that even when the central mass had contracted to

the size of the Earth's orbit it must still have taken 3,181 years. With such slow motion the centrifugal forces would never have overbalanced the central attraction and no rings could have been abandoned.

A few years later (1864) KIRKWOOD showed, from the extreme tenuity of the original mass, that it could have possessed no power of resistance to the slightest strain. Hence the surface of the nebula would have been in continual process of disintegration,—that is, matter would have been abandoned by the nebula continuously and not in rings occasionally.

Of late years the development of the kinetic theory of gases has been the source of fresh arguments against LAPLACE'S hypothesis.

Perhaps the strongest summary of all the objections to the theory that have so far appeared is to be found in the papers of Professors CHAMBERLIN and MOULTON in recent numbers of the *Astrophysical Journal*, the *Journal of Geology*, and the year-books of the Carnegie Institution.

Doubts first arose in the minds of these investigators as to whether the attractive force of the Earth-Moon nebular ring would be sufficient to prevent the lighter gases, such as hydrogen and helium, from escaping into outer space. Reasoning from the kinetic theory of gases and the molecular velocities established by experiment, they concluded that it was very doubtful whether any matter, even that having the lowest molecular activity, could have been retained by such a ring. They were then led to examine the whole theory critically and to test its various assumptions by an appeal to known mechanical laws.

To give the theory every benefit in this investigation, the special assumptions of LAPLACE as to temperature and physical condition of the original nebula were disregarded and the theory taken only in its broadest outlines,—namely, that the matter now in the solar system was once in a gaseous or meteoroidal state and then filled *Neptune's* orbit and formed a spheroidal-shaped mass. If the matter was in the gaseous state, the only further condition imposed is that it was in hydrodynamic equilibrium, rotating practically as a solid with an angular velocity equal to that of our planet *Neptune*. If

the matter was meteoroidal in its condition, then it is assumed that the assemblage of meteoroids behaved sensibly like a mass of gas, an assumption that DARWIN has shown to be valid. In either case the primitive mass was a spheroidal nebula. This nebula was not subject to the action of any external forces, but contracted under its own gravitation, and as it did so it either left off successive rings or divided by some fission process, and the detached masses collected and formed planets and satellites.

Even in these broad outlines, Messrs. CHAMBERLIN and MOULTON find it impossible to uphold the theory. The objections they raise to it are classed in three categories: I. Comparison of observed phenomena with those which would result from the expressed or implied conditions maintained by the hypothesis; II. Answers to the question whether the supposed initial conditions could have developed into the existing system; III. Comparison of those properties of the supposed initial system with the one now existing which are invariant under all changes resulting from the action of internal forces.

Into the first category fall such anomalies as the high inclination of the orbits of *Uranus* and *Neptune*, which have been already mentioned, and the fact that *Mercury* departs more from the average inclination of the planetary system than any other planet, whereas by the theory the planes of the planets' orbits ought to be more nearly coincident as we approach the Sun.

The rapid revolution of *Phobos* relatively to the rotation time of *Mars*, which has been noted above, is also brought forward under this head. This anomaly was ingeniously accounted for by G. H. DARWIN, who reasoned that as the solar tidal friction would serve to retard the planet's rotation without affecting the satellite's orbital motion, it might well be that the revolution period of *Phobos* represented the rotation time of *Mars* at the time the *Phobos* ring of matter was abandoned by the planet. Accepting this explanation, Dr. MOULTON shows that a still more serious difficulty of the same kind is found in the motion of the inner ring of *Saturn*, for this ring revolves nearly twice as fast as the planet rotates, and at *Saturn's* distance from the Sun the solar tides are so feeble

and ineffective that it would require several thousand times as many years to produce the present relation between the two motions in the Saturnian system as that between the motions of *Mars* and *Phobos*.

Another strong objection falling into this category is founded upon the distribution of mass in the solar system. On the assumption of anything like homogeneity in the original nebular mass, the densities of the successive planetary rings ought to be approximately the same, or, if the primitive nebula grew denser towards its center under the pressure of its own gravitation only, the planetary rings ought to increase in density with a certain degree of regularity as we approach the Sun. Assuming that each planet was formed from a ring extending halfway to the two adjacent planets, we can calculate the density of these rings. Making this calculation, and taking the density of the Earth-Moon ring as unity, we find:—

Mercury......	0.015	Jupiter	0.609
Venus........	1.010	Saturn	0.028
Earth........	1.000	Uranus	0.0012
Mars.........	0.003	Neptune	0.0008

This argues a degree of heterogeneity in the original nebula that seems decidedly at variance with the conditions assumed by the Laplacian hypothesis.

The first two arguments advanced in the second category we have already touched upon,—namely, first, that on the kinetic theory of gases the lighter gases would in all probability have escaped from the original nebula, and all the atmospheric gases and water-vapor would certainly have been lost by the Earth-Moon ring, for its gravitative control would have been far less than that of the Moon at present, and this has practically neither water nor atmosphere; second, that in its original volume the solar nebula must have been so extremely tenuous (on assumptions that make the value too great, the density was found to be only 1-191,000,000,000 that of water) that its separate particles, under the conditions postulated by the theory, could have had no appreciable cohesion, especially at the surface, and that hence the matter would have been left behind continuously from the beginning of the process of contraction and no rings could have been formed. But assuming that the gases did not escape, and that rings were formed, could

the rings contract into planets? The answer is that they could not. It is shown that the probabilities of the union of even the largest bodies that could be supposed to exist in a planetary ring would be very slight indeed, and that even in the event that the greater part of the matter of a ring should be concentrated into a roughly spherical mass, the planet could not complete itself by gathering up the remaining matter of the ring.

The objections so far raised are serious enough, but when to them is added the one advanced in the third category the fundamental assumptions of LAPLACE's hypothesis are seen to be invalid, and practically nothing is left of his theory except the very general conclusion that our present system originated in a nebula. This final argument is based on the theorem in mechanics which says that the moment of momentum of a system of particles undisturbed by external forces remains constant, no matter what changes may result within the system in consequence of the action of internal forces. By "moment of momentum" we mean the product of the masses of all the particles multiplied by their velocities and by their perpendicular distance from the axis of the system; and this product is always the same, no matter how the particles may rearrange themselves, provided the system is not disturbed by external forces.

It follows that the moment of momentum of the present solar system must be the same as that possessed by the original nebula. The present moment of momentum can be calculated with a high degree of accuracy. To calculate that of the original nebula, assume that it extended only to the orbit of *Neptune,* not beyond it, that it was spherical instead of spheroidal, and that its density followed the law developed by LANE, RITTER, HILL, DARWIN, Lord KELVIN, and others. These assumptions are all favorable to the Laplacian hypothesis; but when the calculations are made it is found that the moment of momentum of the original system must have been fully 213 times as great as that of the system as it exists at present. And, further, it appears that this ratio was not even constant during the process of solar evolution. For when the nebula had shrunk to *Jupiter's* orbit it was 140 to 1, when the

central mass was confined within the Earth's orbit the ratio was 1208 to 1, and at the Mercurial stage 754 to 1. Such variations preclude the possibility of systematic errors of computation, while the amount of the discrepancy cannot be accounted for by any error in the assumed law of density or by the approximations used to shorten the numerical process, but, in MOULTON's words, "it points to a mode of development quite different from, and much more complicated than, that postulated in the nebular theory under discussion."

But if the Laplacian nebula is thus eliminated, what is to take its place as primal ancestor of our Sun?

An answer has been given to this question within the past few months, and while it is at present only advanced tentatively, it seems to meet the requirements so fully as to entitle it to a high degree of confidence.

The spectroscope has shown that the green nebulæ, which include those stellar and planetary forms which HERSCHEL thought to be next to the last stage of the genetic process by which irregular nebulæ become stars, and which afforded LAPLACE types of the primal solar nebula, consist largely of hydrogen, helium, and nebulium, with traces of a few other non-metallic elements, all in the gaseous, or free molecular state. No traces of metals are to be found in them.

The white nebulæ, on the other hand, give continuous spectra, and this is generally interpreted to mean that the luminous matter composing them is in the solid or liquid state, or gaseous under high pressure,—that the molecules, in other words, are in the aggregated state in distinction to the free state found in the green nebulæ. It is probable that the matter is in the solid state, but very finely divided, for the immense volume and the extreme tenuity seem conclusive arguments against the liquid form. What the chemical composition of these molecules is the spectroscope does not reveal to us.

Now, the white nebulæ include all the great spirals, and the work done by Professor KEELER with the Crossley reflector of the Lick Observatory proves that the nebulæ are not only far more numerous than had hitherto been supposed (Professor KEELER estimated the number at not less than 120,000) but that the typical nebular form is the spiral.

The significance of Professor KEELER's work cannot be better stated than in his own words. He says:—

"While I must leave to others an estimate of the importance of these conclusions, it seems to me that they have a very direct bearing on many, if not all, questions concerning the cosmogony. If, for example, the spiral is the form normally assumed by a contracting nebulous mass, the idea at once suggests itself that the solar system has been evolved from a spiral nebula, while the photographs show that the spiral nebula is not, as a rule, characterized by the simplicity attributed to the contracting mass in the nebular hypothesis."

This suggestion of Professor KEELER's has been taken up by Professors CHAMBERLIN and MOULTON, who have endeavored to develop an adequate theory of solar evolution from a spiral nebula.

The very appearance of such nebulæ is suggestive. Their most significant feature is the presence of two dominant arms arising from opposite sides of the central mass. They are disklike, and the matter contained in them is obviously very irregularly distributed, just as it is in our system. In fact, everything seems to indicate that they are governed by some system of combined kinetic energy and gravitation, which while exercising a general control of the whole, permits independence of its parts.

A spiral nebula, however, seems to show that it is not an original form, but that it was developed from some antecedent body. Naturally, we cannot go back from form to form in our search for the ultimate origin of matter; but it is interesting to note that a spiral nebula might have been formed from an antecedent sun by processes not unlikely to be realized among the stars. The collision of two suns, for example, is not impossible, and the passage of two suns within relatively small distances of each other is far from being an improbable event.

Now, our Sun, as we learn from observation, is the seat of violent activities. Prominences or protuberances are shot out thousands of miles above its surface with velocities sometimes as great as 300 miles per second. Only the enormous gravitative power residing in the Sun could balance the expansive potency of these elastic forces. But let another body—a larger sun—make a close approach to our Sun; then, on the principle of tidal forces, gravity would be relieved along the line of mutual attraction, and two exceptional protuberances

on opposite sides would arise, converting the Sun into a two-branched spiral. The two suns would swing about each other in sharp curves and the protuberances being differentially affected by the attraction of the companion sun would move in different curves, and thus rotatory motion would be initiated.

To account for our planetary system it is unnecessary to assume that the antecedent sun was entirely disrupted; it would be amply sufficient if under the influence of such a disruptive approach as that outlined only one or two per cent of its mass were dispersed in this manner, for the combined mass of the planets is only about one seven-hundredth that of the Sun.

But in the case of such a disruptive approach it is hardly possible that there would be only one outburst from the Sun. It is practically certain, on the contrary, that as the Sun was more and more affected by the differential attraction of its companion, and as the directions of attraction varied with the relative motion of the two bodies, there would be a succession of outbursts more or less pulsatory in character, resulting in two irregularly divided arms, along which the matter ejected would be distributed in larger or smaller knots connected by the more widely dispersed material. These knotty masses in turn would probably possess more or less rotatory motion, and the outer ones, being formed from the surface material of the Sun, would have a lower specific gravity than the inner ones which would originate from the lower depths.

"It is thus conceived [says Professor CHAMBERLIN] that a spiral nebula, having two dominant arms opposite one another, each knotty from irregular pulsations and rotatory, the knots probably also rotatory, and attended by subordinate knots and whirls, together with a general scattering of the larger part of the mass in irregular nebulous form, would arise from the simple event of a disruptive approach.

"The ejected matter at the outset must have been in the free molecular state, since, by the terms of the hypothesis, it arose from a gaseous body; but the vast dispersion and the enormous surface exposed to radiation doubtless quickly reduced the more refractory portions to the liquid and solid state, attended by some degree of aggregation into small accretions; hence the continuous spectrum which this class of nebulæ presents."

Of course, this is only one way out of many in which a spiral nebula might be formed, and the further elaboration of the theory does not all depend upon this particular genetic

history. It is sufficient to show that a spiral nebula might originate from a previously existing sun by a series of events not impossible and perhaps not unlikely to happen.

Assuming, then, a spiral nebula as our initial form, we note at once three conspicuous elements: (1) the central mass, obviously the future sun; (2) the knots on the arms, the nuclei of the planets; and (3) the diffuse matter, material for the growth of sun and planets. In the parent nebula of our own system the central mass must be assumed very great relatively, the knots to be irregular in size and placed at irregular distances from the center, and the mass of diffused matter to be very small compared to the central mass, but probably quite large as compared with the knots.

What will be the properties of a system formed from such a nebula? As developed by Dr. MOULTON, they are as follows:—

(1) The planets will all revolve in the same direction and in nearly the same plane;

(2) The sun will rotate in this same direction, and will have an equatorial acceleration;

(3) The more the planets grow the more nearly circular will their orbits become;

(4) The planets will rotate in a forward direction and nearly in the plane of the orbit;

(5) The more a planet grows, the more rapidly will it rotate;

(6) A planet may at first have many satellite nuclei, revolving in any direction, but the scattered material, acting as a retarding medium, will tend to drive all those nuclei not moving forward in the general plane of the system down upon their primary;

(7) The scattered material will develop and preserve circularity in satellite orbits having direct or forward motion of revolution, but will tend to make considerably eccentric the orbits of those in retrograde motion;

(8) A satellite may revolve more rapidly than its primary rotates;

(9) The system may have many planetoids (or asteroids) of interlocking orbits; the orbits of these bodies will be likely to present much greater deviations from the general plane of the system than those of the larger planets;

(10) The smaller planets will be cool and dense, the large ones hot and tenuous;

(11) The greater part of the mass will be found in the central Sun, but the greater part of the moment of momentum will belong to the planets.

Clearly, if a system possessing these properties can be shown to follow necessarily from the assumed spiral nebula, or even if, by reasoning based on known mechanical and mathematical principles, it can be logically deduced from such an initial state, there can be no question about the standing of the theory. For it explains very nearly all the observed relations in the solar system and is contradicted by none.

It would take us too far to follow the details of the arguments that have been presented in proof of the theory, but it must be said that they seem to be entitled to great weight. The propounders of the theory do not claim that they have as yet brought forward enough evidence fully to establish it; in fact, they distinctly state that they are devising further tests to apply to it and are investigating as fully as possible all the direct and indirect consequences likely to follow from the assumptions they have made. The evidence they present makes it already a good working hypothesis, for it explains as much as did the ring theory of LAPLACE, and also those phenomena that contradicted the latter, and nothing has yet been found to seriously question its validity.

Professor CHAMBERLIN, who is more interested in the geological bearings of the theory, thinks it affords a rational explanation of the development of the Earth's atmosphere and hydrosphere and of the distribution of land and water, as well as of the phenomena of glaciation and vulcanism, of the carboniferous era, and of other difficult questions that beset the inquiries of geologists.

The most interesting contribution of the theory, however, is, as Professor MOULTON intimates, to the general philosophy of nature, for it shows important tendencies toward a dispersion of matter as well as toward its aggregation, and thus points to a cyclical character in the evolution of celestial bodies. The fundamental question that must be answered before we can fully accept the theory is, What is the source

of the energy necessary to maintain any system through such an endless cycle of changes? A few years ago not even the hint of an answer would have been forthcoming, but the recent revolutionary discoveries of chemists and physicists as to the constitution of matter suggest the idea that the internal energies of the atoms, especially under such conditions as those existing in the Sun or a star, will prove adequate to all the requirements.

ASTRONOMICAL OBSERVATIONS IN 1905.

MADE BY TORVALD KÖHL, AT ODDER, DENMARK.

VARIABLE STARS.

Z Cygni.[1]

Jan. 1:	$Z <$ e.	Aug. 21:	id.
7:	id.	24:	id.
13:	= e.	Sept. 15:	$<$ e.
22:	= d.	17:	id.
Feb. 2:	= c.	Oct. 1:	id.
12:	= b.	28:	$>$ c. $<$ b.
26:	= a.	Nov. 18:	= a.
Mar. 2:	1 step $>$ a.	27:	1 step $>$ a.
May 5:	= d.	30:	= a.
13:	$<$ d. $>$ e.	Dec. 16:	id.
25:	= e.	18:	$<$ a. $>$ b′.
Aug. 6:	1 step $<$ e.	26:	id.
11:	$<$ e.	31:	id.
17:	id.		
20:	id.		

S Ursæ Majoris.[2]

Jan. 1:	$S =$ e.	Feb. 2:	id.
5:	1 step $>$ d.	12:	id.
7:	= d.	26:	2 steps $<$ e.
10:	2 steps $>$ d.	Mar. 2:	id.
12:	= d.	24:	1 step $>$ f′.
13:	1 step $>$ d.	Apr. 1:	= f.
22:	2 steps $>$ d.	3:	$<$ f. $>$ g.
31:	= d.		

[1] *Vide* the sketch in the *Publications* A. S. P., No. 100, page 16.

[2] *Vide* the sketch in the *Publications* A. S. P., No. 73, page 56.